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Fuel cells, an alternative to standard sources of energy

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Abstract

Three E's are the national energy policy drivers of any country of the world, **E**nergy security, **E**conomic growth and **E**nvironmental protection. A fuel cell is an energy conversion device that produces electricity by electrochemically combining fuel (hydrogen) and oxidant (oxygen from the air) gases through electrodes and across an ion conducting electrolyte. The principal characteristic of a fuel cell is its ability to convert chemical energy directly into electrical energy giving much higher conversion efficiencies than any conventional thermo-mechanical system thus extracting more electricity from the same amount of fuel, operate without combustion so they are virtually pollution free and have quieter operation since there are no moving parts. The emission of fuel cells running on hydrogen derived from a renewable source will be nothing but water vapour. Fuel cells are presently under development for a variety of power generation applications in response to the critical need for a cleaner energy technology. This paper reviews the existing or emerging fuel cells technologies, their design and operation, their limitations and their benefits in connection with energy, environment and sustainable development relationship. Few potential applications of fuel cell will be discussed. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

It is a well known fact that eight countries have 81% of all world crude oil reserves, six countries have 70% of all natural gas reserves and eight countries have 89% of all coal reserves. The global warming situation is worsened by the fact that power generation is continuously increasing throughout the world using such a fossil fuel. Additionally, the world population keeps increasing at 1.2–2% per year, so that it is expected to double by the middle of the 21st century. Therefore, in the year 2050, the world population is expected to reach 12 billions. Economic development will almost certainly continue to grow as a consequence and global demand for energy services is expected to increase by as much as an order of magnitude in 2050, while primary energy demands are expected to increase by 1.5–3 times as shown in Fig. 1 [1].

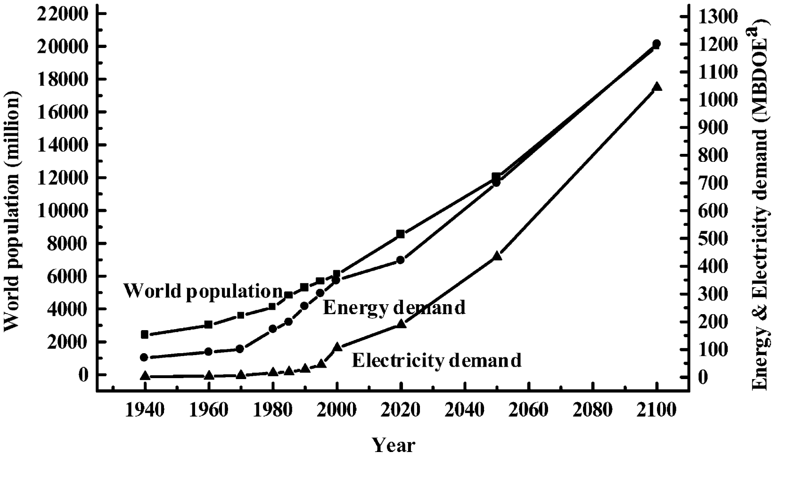

Fig. 1. Actual and estimated world population, energy and electricity demands ([a]Millions of barrels per day of oil equivalent).

It is also now well established that global warming, due to effluent gases emission and CO_2 in particular, is happening and according to the three well known centres assessing this phenomenon in the world, Princeton in the USA, Hamburg in Germany and IPCC of London in the UK, the air temperature rise during the last 70 years is 2.3, 1.3 and 1.7 °C respectively. Moreover, from the US National Oceanic and Atmospheric Administration and the Scripps Institute of Oceanography in San Francisco, the average temperature of the Atlantic, Pacific and Indian Oceans (covering 72% of the earth surface) has risen by 0.06 °C since 1995. Table 1 estimate the global climate change around 2050 and shows an example of CO_2 emissions (in tonnes) per head of population in ten regions of the world [2].

It is worth noticing that the USA produces five times the world average emission and according to the US Environmental Protection Agency, motor vehicles in the USA account for 78% of all CO_2 emissions. World wide, over one billion people living in urban areas suffer from severe air pollution, and, according to the World Bank, over 700,000 deaths result each year [3]. Moreover, each gallon of gasoline produced and used in an internal combustion engine releases roughly 12 kg of CO_2, a greenhouse gas that contributes to global warming. Estimates of future data suggest that developing countries are the fastest growing source of CO_2 emissions in that 17 major developing countries will reach the emission level of 3.6 billion tonnes in 2025 compared to 0.9 billion tonnes in 1985. This can be reduced through efficiency improvements and fuel-switching measures. These observations and others [4] demonstrate that interest will likely increase regarding energy related environment concerns and that energy is one of the main factors that must be considered in discussions of sustainable development since the existing intimate connection between energy, the environment and the sustainable development. In response to the critical need for a cleaner energy technology, some potential solutions have evolved including energy conservation through improved energy efficiency, a reduction in the fossil fuels and an increase in the supply of environmentally friendly energies forms which is leading to the use of renewable sources (water, sun, wind, biomass, geothermal, hydrogen) and technologies and an alternative to standard source of energy: the fuel cells.

Table 1
Global climate change estimate around 2050 and CO_2 emissions (tonnes/capita)

Scenario	T increase (°C)	Seas level rise (cms)	CO_2 concentration (ppmv)
Low	0.9	12	467
Medium	1.8	22	498
High	2.4	67	528

USA	Australia	Japan	E.U.	USSR	M.East	China	L.America	Asia	Africa	World average
19.88	15.84	9.17	8.58	8.48	5.31	2.51	2.11	1.21	0.98	3.92

2. Fuel cell

A fuel cell is an energy conversion device that generates electricity and heat by electrochemically combining a gaseous fuel (hydrogen) and an oxidant gas (oxygen from the air) through electrodes and across an ion conducting electrolyte. During this process, water is formed at the exhaust. The fuel cell does not run down or require any recharging, unlike a battery it will produce energy as long as fuel is supplied. The principle characteristic of a fuel cell is its ability to convert chemical energy directly to electrical energy giving much higher conversion efficiencies than any conventional thermo–mechanical system thus extracting more electricity from the same amount of fuel, to operate without combustion so they are virtually pollution free and have quieter operation since there are no moving parts.

3. Historical notes

Fuel cells are an old technology. Problems have plagued their introduction. Alessandro Volta (1745–1827) was the first scientist to place the observations of the electrical phenomena on a scientific footing. J. W. Ritter (1776–1810) also known as the founder of the electrochemistry, has continued to develop the understanding of electricity. Sir Humphrey Davy created, in 1802, a simple fuel cell based upon a compound (C/H_2O, $NH_3/O_2/C$) delivering a feeble electric shock. The discovery of the principle of the fuel cell is due to Christan Friedrich Schönbein, Professor at the University of Bâle from 1829 to 1868. In 1839 Sir William Grove, a British lawyer and physicist, created the first cell type based on reversing the electrolysis of water [5]. Ceramic fuel cells came much later and began with Nernst's discovery of solid oxide electrolytes in 1899 [6] and the operation of the first ceramic fuel cell at 1000 °C by Baur and Preis in 1937 [7]. Since 1945, three research groups (USA, Germany and former USSR) took over the studies on some principal types of generators by improving their technologies for industrial development purpose. These works yielded the actual concepts, namely at Siemens and Pratt & Wittney [8]. In connection with the space program Apollo in 1960, NASA spent tens of millions of dollars in a successful program that used hydrogen based fuel cells to power the on-board electrical systems on the Apollo journey to the moon. Beginning in the mid-1980s, government agencies in the USA, Canada and Japan significantly increased their funding for fuel cell R&D. Starting in the 1990 Ballard, a leader in fuel cells making, put its fuel cells into a series of increasingly impressive prototype buses that run on compressed hydrogen. The first small bus rolled out for the media in 1993. In the late 1990s, six Ballard-built fuel cell transit buses were put onto the street of Chicago and Vancouver. Today, fuel cells are common in spaceflight, transportation and make sense for use as portable power, home power generation and large power generation.

4. Design and operation of the fuel cell

A fuel cell consists of two electrodes sandwiched around an electrolyte. Hydrogen fuel is fed into the anode of the fuel cell and oxygen, from the air, enters the cell through the cathode. The hydrogen, under the action of the catalyst, splits into protons (hydrogen ions) and electrons, which take different paths towards the cathode. The proton passes through the electrolyte and the electron create a separate current that can be used before reaching the cathode, to be reunited with the hydrogen and oxygen to form a pure water molecule and heat as shown in Fig. 2.

4.1. Parameters of the fuel cell

The fuel cell is mainly composed of two electrodes, the anode and the cathode, the catalyst, and an electrolyte. The fuel is also important as the principal parameter but independent of the other as it is most of the time converted into hydrogen. The main function of the electrode is to bring about reaction between the reactant (fuel or oxygen) and the electrolyte without itself being consumed or corroded. It must also bring into contact the three phases i.e. the gaseous fuel, the liquid or solid electrolyte and the electrode itself. The anode, used as the negative post of the fuel cell, disperses the hydrogen gas equally over the whole surface of the catalyst and conducts the electrons, that are freed from hydrogen molecule, to be used as a useful power in an external circuit. The cathode, the positive post of the fuel cell, distributes the oxygen fed to it onto the surface of the catalyst and conducts the electrons back from the external circuit where they can recombine with hydrogen ions, passed across the electrolyte, and oxygen to form water. The catalyst is a special material that is used in order to facilitates the reaction of oxygen and hydrogen. This can be a platinum coating as in Proton Exchange Membrane or nickel and oxide for the Solid

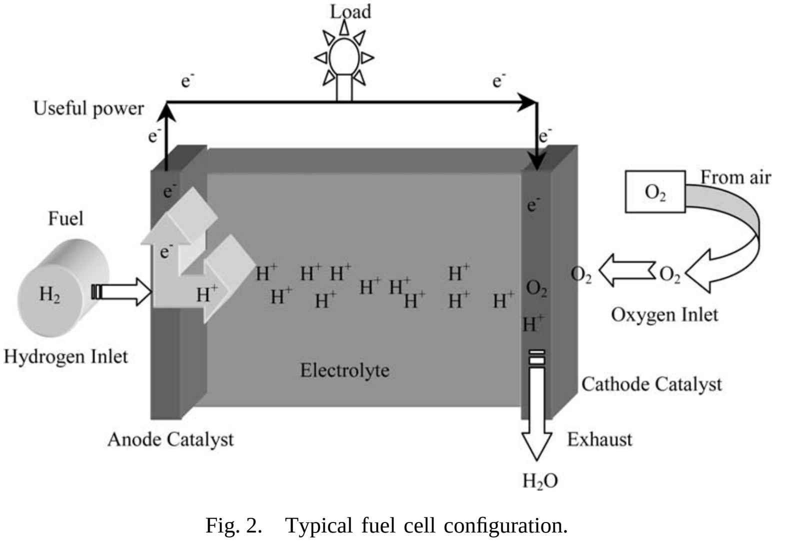

Fig. 2. Typical fuel cell configuration.

Table 2
Technical characteristics of different fuel cells

Types	Electrolyte	Operating T (C)	Fuel
Alkaline (AFC)	Potassium hydroxide (KOH)	50–200	Pure hydrogen, or hydrazine
Direct methanol (DMFC)	Polymer	60–200	Liquid methanol
Phosphoric acid (PAFC)	Phosphoric acid	160–210	Hydrogen from hydrocarbons and alcohol
Sulphuric acid (SAFC)	Sulphuric acid	80–90	Alcohol or impure hydrogen
Proton-exchange membrane (PEMFC)	Polymer, proton exchange membrane	50–80	Less pure hydrogen from hydrocarbons or methanol
Molten carbonate (MCFC)	Molten salt such as nitrate, sulphate, carbonates...	630–650	Hydrogen, carbon monoxide, natural gas, propane, marine diesel
Solid oxide (SOFC)	Stabilised zirconia and doped perovskite	600–1000	Natural gas or propane
Solid polymer (SPFC)	Solid sulphonated polystyrene	90	Hydrogen

Oxide fuel cells. The nature of the electrolyte, liquid or solid, determines the operating temperature of the fuel cell. It is used to prevent the two electrodes, by blocking the electrons, to come into electronic contact. It also allows the flow of charged ions from one electrode to the other. It can either be an oxygen ion conductor or a hydrogen ion (proton) conductor, the major difference between the two types is the side in the fuel cell in which the water is produced: the oxidant side in proton-conductor fuel cells and the fuel side in oxygen-ion-conductor ones.

4.2. Types of fuel cells

The fuel cells are sorted by their operating temperature and their classification is generally done according to the nature of the electrolyte used. There are several types of fuel cell technologies being developed for different applications, each using a different chemistry, as summarised in Table 2.

Table 3
Fuel cell air emissions from 1 year of operation

Air emissions[a]	SO_X	NO_X	CO	Particles	Organic compounds	CO_2
Fossil fuelled plant	28,000	41,427	28,125	500	468	4,044,000
Fuel cell	0	0	72	0	0	1,860,000

[a] Pounds of emissions per 1650 MWh from one year full operation

Table 4
Fuel cell's operation sound effect

Means	Gas-electric	Microturbine	Diesel-electric	Fuel cell	Social conversation
Sound level	high	moderate	high	low	low[a]
Sound proofing	required	required	required	not required	not required

[a] Similar to fuel cell sound level

Table 5
Fuel cell efficiency

Means	Gas-electric	Microturbine	Diesel-electric	Fuel cell
Efficiency	20%	24%	32%	90% with heat recovery

There are also other types of fuel cells which are less employed but may later find a specific application, for example, the air-depolarised cells, sodium amalgam cells, biochemical fuel cells, inorganic redox cells, regenerative cells, alkali metal–halogen cells etc.

Practical fuel cells can be combined to form a fuel cells' stack. The cells are connected in electrical series to build a desired output voltage. An interconnect component connects the anode of one cell to the cathode of the next cell in the stack. A fuel cells' stack can be configured in series, parallel, series–parallel or as single units, depending upon the type of applications. The number of fuel cells in a stack determines the total voltage, and the surface of each cell gives the total current.

4.3. Fuel cell benefits and limitations

- Energy security: reduce oil consumption, cut oil imports, and increase the amount of the country's available electricity supply.
- Reliability: achieves operating times in excess of 90% and power available 99.99% of the time.
- Low operating cost: the efficiency of the fuel cell system will reduce drastically the energy bill (in the case of a mass production of fuel cells).
- Constant power production: generates power continuously unlike backup generators, diesel engines or Uninterrupted Power Supply (UPS).
- Choice of fuel: allows fuel selection, hydrogen may be extracted from natural gas, propane, butane, methanol and diesel fuel.
- Clean emissions: 100–1000 times cleaner than the 1998 American clean bus standards (15 ppmv of CO_2) [9] and compared with traditional combustion power plants [10]:stops NO_X and SO_2 from being released into environment therefore

eliminates 20,000 kg of acid rain and smog-causing pollutants from the environment and reduce carbon dioxide emissions by more than two million kg per year.
- Quiet operations: quiet enough to be installed indoors, normal conversation possible near to fuel cell, and hearing protection is not required as for the combustion engines.
- High efficiency: converts up to 50–70% of available fuel to electricity (90% with heat recovery [10]) and reduces fuel costs and conserves natural resources.

The fuel cell uses oxygen and hydrogen to produce electricity. The oxygen comes from the air (present at around 20%) unlike the hydrogen which is difficult to store and distribute and this is the reason for which hydrocarbon or alcohol fuels, readily available, are used. A reformer is therefore needed to turn these products into hydrogen, which is then fed to the fuel cell. Some of the fuel cells have problems with electrolyte management (liquid electrolytes, for example, which are corrosive and difficult to handle), others use expensive material such as platinum as in the PEMFCs, need hydration of their electrolyte material or have a high operating temperature which is the case of the SOFCs and MCFCs.

4.4. Fuel cell developments

Present material science has made the fuel cells a reality in some specialised applications. By far the greatest research interest throughout the world has focussed on Proton Exchange Membrane and Solid Oxide cell stacks. PEMs are a well advanced type of fuel cell that are suitable for cars and mass transportation if they can be made cost competitive. Their efficiency is around 50% which is better than any internal combustion engine. Efforts made by DLR, a German aerospace research body, has resulted in a reduction of the amounts of noble metal catalyst needed in PEMFCs and DMFCs to less than 0.05 mg/sqcm by engineering extremely thin reactive layers [11]. A thin layer tends to be more efficient since it promotes reaction and allows the passage of product water. As for the future development of SOFCs, having an efficiency around 70% with a heat conversion possibility, it is mainly concerned with reducing their operating temperature since expensive high temperature alloys are used to house the fuel cell. The reduction in the temperature will therefore allow the use of cheaper structural components such as stainless steel. A lower temperature will also ensure a greater overall system efficiency and a reduction in the thermal stresses in the active ceramic structures, leading to a longer expected lifetime of the system, and making possible the use of cheaper interconnect materials such as ferritic steels, without protective coatings. In the DLR's process, Ceramics that are currently being developed, by researchers around the world, to replace the actual yttria-stabilised zirconia (YSZ) include scandium-stabilised zirconia (ScSZ), samarium-doped ceria, gadolinium-doped ceria (Gd-doped CeO_2), $Ba_2In_2O_5$, in addition to perovskite ceramic such as $BaCe_{0.9}Gd_{0.1}O_3$, $CaAl_{0.7}Ti_{0.3}O_3$ and $SrZr_{0.9}Sc_{0.1}O_3$ [12]. Doped lanthanum gallate, in particular (SrMg)–doped $LaGaO_3$, appears to show promise as an SOFC solid electrolyte. New ways are also sought to deposit electrolyte film very thinly in order to minimise ohmic losses and reduce

costs. A range of ceramic perovskite that includes the oxide of lanthanum compounded with gallium scandium, indium and aluminium for cathode material purposes, are also produced.

4.5. Applications of fuel cells

Fuel cells could be used in many applications. Each proposed use raises its own issues and challenges. Fuel cells' most needed uses are:

- High power reliability: computer facilities, call centres, communication facilities, data processing centres high technology manufacturing facilities.
- Emission minimisation or elimination: cars, buses, urban areas, industrial facilities, airports, zones with strict emissions standards.
- Limited access to utility grid: rural or remote areas, maximum grid capacity.
- Biological waste gases are available: waste treatment plants, fuel cells can convert waste gases to electricity and heat with minimal environment intrusion.

5. Conclusion

Already around 1900 scientists and engineers were predicting that fuel cells would be common for producing electricity and motive power within a few years. Nowadays fuel cells provide highly efficient, pollution free power generation. Their performance has been confirmed by successful operation power generation systems. Electrical-generation efficiencies of 70% are possible along with a heat recovery possibility. In the near future, technology will open up new possibilities and fuel cell based power systems will be ideal distributed power-generation systems: reliable, clean, quiet, environmentally friendly, and fuel conserving.

The governing body of the United Nations' Global Environment Facility (GEF) has recently given the go-ahead for a demonstration project that is expected to demonstrate clean fuel cell city buses in five developing countries; Brazil, Mexico, Egypt, India and China [13].

Acknowledgements

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